

PL-TR-97-2012

**APPLICATION OF PARALLEL COMPUTING
ALGORITHMS TO THREE-DIMENSIONAL MODELING
OF SEISMIC WAVES GENERATED BY COMPLEX
SOURCES IN INHOMOGENEOUS MEDIA**

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15 January 1997

**Final Technical Report
14 July 1995–30 November 1996**

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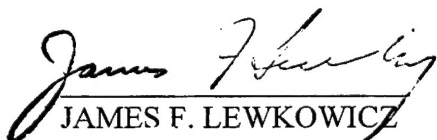
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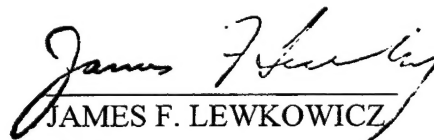


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This technical report has been reviewed and is approved for publication.


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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 15 JAN 1997	3. REPORT TYPE AND DATES COVERED Final Technical 7/14/95-11/30/96		
4. TITLE AND SUBTITLE Application of Parallel Computing Algorithms to Three-Dimensional Modeling of Seismic Waves Generated by Complex Sources in Inhomogeneous Media		5. FUNDING NUMBERS F19628-95-K-0008		
6. AUTHOR(S) Charles G. Doll, Jr. Joseph R. Matarese Bertram Nolte		PE 62101F PR 7600 TA GM WU AA		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Earth Resources Laboratory Dept. of Earth, Atmospheric, and Planetary Sciences Massachusetts Institute of Technology 42 Carleton Street Cambridge, MA 02142		8. PERFORMING ORGANIZATION REPORT NUMBER 63614		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Phillips Laboratory 29 Randolph Road Hanscom AFB, MA 01731-3010 Contract Manager: Delaine Reiter/GPE		10. SPONSORING/MONITORING AGENCY REPORT NUMBER PL-TR-97-2012		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) We describe a hardware upgrade that was performed on the nCUBE 2 massively parallel computer at MIT's Earth Resources Laboratory. The upgrade involved the installation of additional memory, additional disk space, and an additional small nCUBE 2 computer. The reason for performing the upgrade was to provide ERL with a computational environment suitable for conducting large-scale 2-D and 3-D wave propagation simulations. We also describe two recent projects that were performed on the upgraded nCUBE 2. One project was a 3-D simulation of earthquake-generated ground motion in the Boston Basin. The other project was the development of a parallel irregular-grid modeling code which is well-suited for 2-D modeling of regional wave propagation in the presence of surface topography.				
14. SUBJECT TERMS Parallel computing; 3-D seismic wave propagation; earthquake ground motion			15. NUMBER OF PAGES 20	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR	

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List of Previous and Related Contracts

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DARPA/AFPL Contract F19628-90-K-0057, "Research in Regional Seismology: The Effect of Anisotropy", August 1990 to July 1992.
DARPA/AFPL Contract F29601-91-K-DB15, "Research on Monitoring at Regional Distances", September 1991 to September 1993.
AFOSR Contract F49620-92-J-0413, "Basic Research in Nuclear Test Monitoring", July 1992 to July 1994.
AFOSR Contract F49620-93-1-0424 "Seismic Wave Radiation, Propagation and Event Location in Laterally Heterogeneous Media", July 1993 to December 1994.
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Olsen, K.B., R.J. Archuleta, and J.R. Matarese, 1995, Three-dimensional simulation of a magnitude 7.75 earthquake on the San Andreas Fault, *Science*, 270, 1628-1632.

1. INTRODUCTION

The 512-processor nCUBE 2 massively parallel computer, originally purchased in 1990, was upgraded to provide a capable computing environment for conducting large-scale 2-D and 3-D wave propagation simulations at the M.I.T. Earth Resources Laboratory (ERL). This upgrade involved three major components: (1) additional memory to allow simulations to be conducted on larger earth models; (2) additional disk space to allow detailed results of these simulations to be recorded for further analysis; and (3) an additional, small nCUBE 2 computer to be used ultimately as an Oracle database platform and to enable code development work to continue while large-scale simulations were occupying the big machine. The memory upgrade was performed in late December, 1995, and the disk upgrade and secondary nCUBE 2 installation were performed in the early spring of 1996.

Quantitatively, the memory upgrade increased the nCUBE 2's aggregate memory from 2.75 GB (gigabytes) to 5.375 GB, while the disk upgrade added a 100 GB high performance parallel filesystem. Before the memory upgrade, the nCUBE 2 had 448 processors with 4 MB (megabytes) of RAM each and 64 processors with 16 MB of RAM each. Given this configuration and the nature of the parallel finite difference modeling algorithm used in the wave simulations, the largest models that could be stored in memory, decomposed among all 512 processors, comprised 500 by 500 by 180 grid points. The upgrade has quadrupled the memory on roughly one-half the machine, i.e., the memory on 224 processors was increased from 4 MB to 16 MB. Therefore, the maximum model size has approximately doubled, for

example, a 1000 by 500 by 180 grid can now be stored.

In the course of conducting finite difference simulations, snapshots of the surface particle velocity field are typically recorded at every tenth-time step to provide a record of the surface ground motion. Given the duration of the simulations, the files containing the snapshot data grow to several hundred megabytes of data for each of the three Cartesian components of the particle velocity. The size of the disk array now makes it possible to archive the results of many simulations for comparative analysis. Also, snapshots of particle motion for the entire model volume can be saved, although at 100 MB per snapshot, not at the same rate as with the surface motion.

The following sections describe examples of wave propagation simulation performed on the upgraded nCUBE 2 computer.

2. BOSTON BASIN GROUND MOTION SIMULATIONS

In a previous study (Olsen *et al.*, 1995), a parallel version of a 3-D elastic finite-difference code was run on ERL's nCUBE 2 512-processor computer to simulate earthquake-generated ground motions in the Los Angeles Basin. The purpose was to study site amplification and scattering effects due to the 3-D structure of the basin. Here we report preliminary results of a similar study of the Boston Basin. Using the same finite difference code on our nCUBE 2, we simulated the 3-D ground motions within the Boston Basin generated by a hypothetical earthquake in the basin. The results of some initial simulations for the Boston

Basin suggested that the 3-D structure of the sedimentary basin has a significant effect on the complexity and amplification of surface ground motions. To better understand the basin effects, we have done subsequent simulations, described below, that compare the ground motions resulting from the 3-D basin model with those from a simple, 1-D model (layer over a half-space) that does not contain a 3-D sedimentary basin.

For each earth structure model, seismic waves were simulated for a hypothetical Mw 5.8 earthquake. The earthquake occurs along a vertical, strike-slip fault striking east-west with length 6.0 km and height 3.8 km. The fault centroid (point of initiation of the rupture) is placed at about a 5 km depth, and the fault was allowed to displace 1 meter to the west. For the simulation done with the 3-D basin model, the top of the fault lies 400 meters closer to the surface than for the 1-D model.

Each earth structure model (3-D and 1-D) was gridded with a cell size of 100 meters, which permits adequate sampling of wavelengths down to ~ 600 meters. Given the P propagation velocity of ~ 5000 meters/sec in the sedimentary rock of the basin, the peak frequency of the simulated ground motion is 8 Hz, with a center frequency of 4 Hz. The size of the basin model grid was 401 by 400 by 72 nodes in the east-west, north-south and depth directions, respectively.

The results of the ground motion simulations are shown in Figure 1 (3-D basin model) and Figure 2 (1-D two-layer model). From the top frames of the figures we see that the 3-D basin model produces peak ground velocities that are strongly variable with position on the

BOSTON BASIN

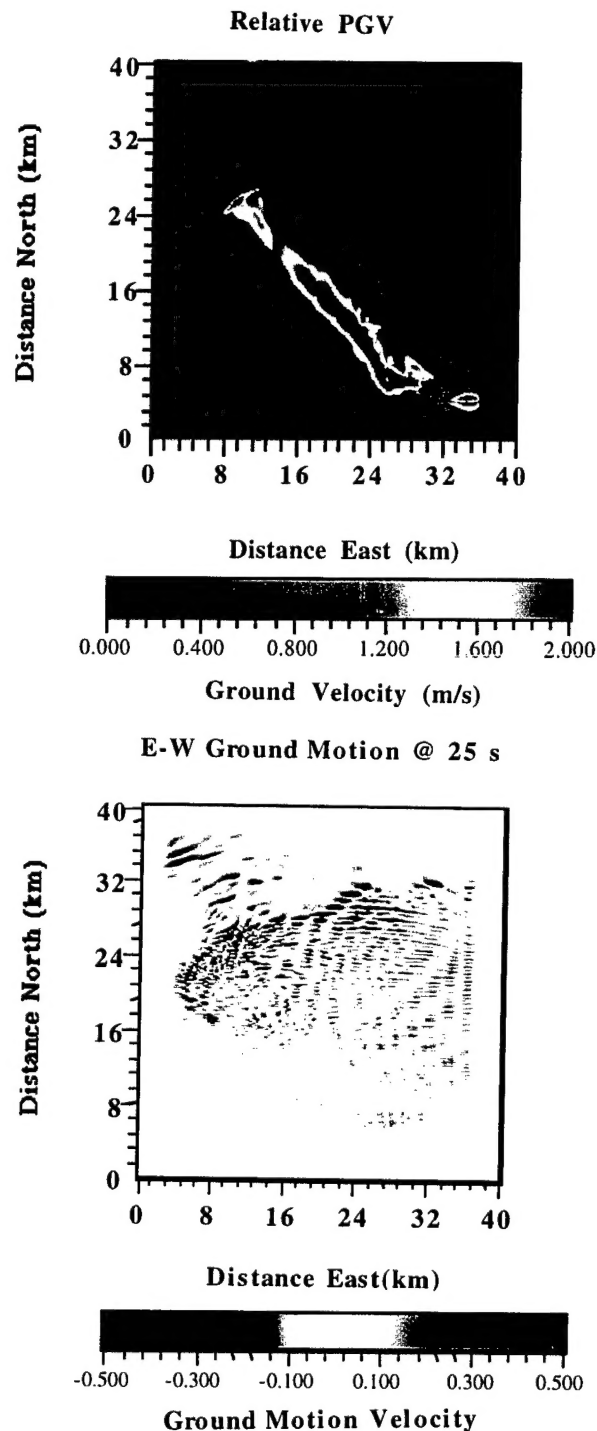


Figure 1: Snapshot of peak ground velocity at the surface of the Boston Basin resulting from an $M_w = 5.8$ earthquake (top). Ground motion at surface 25 seconds after start of rupture (bottom). The source of the earthquake is a vertical strike-slip fault displaced 1 m to the west. The fault has a length of 6 km, a height of 3.8 km, a centroid about 5 km deep, and is located at the southeast edge of the basin (note its lobed radiation pattern at the southeast corner of the basin). The earth model consists of a 3-D basin of sedimentary rock and irregular geometry surrounded by hard rock (granite).

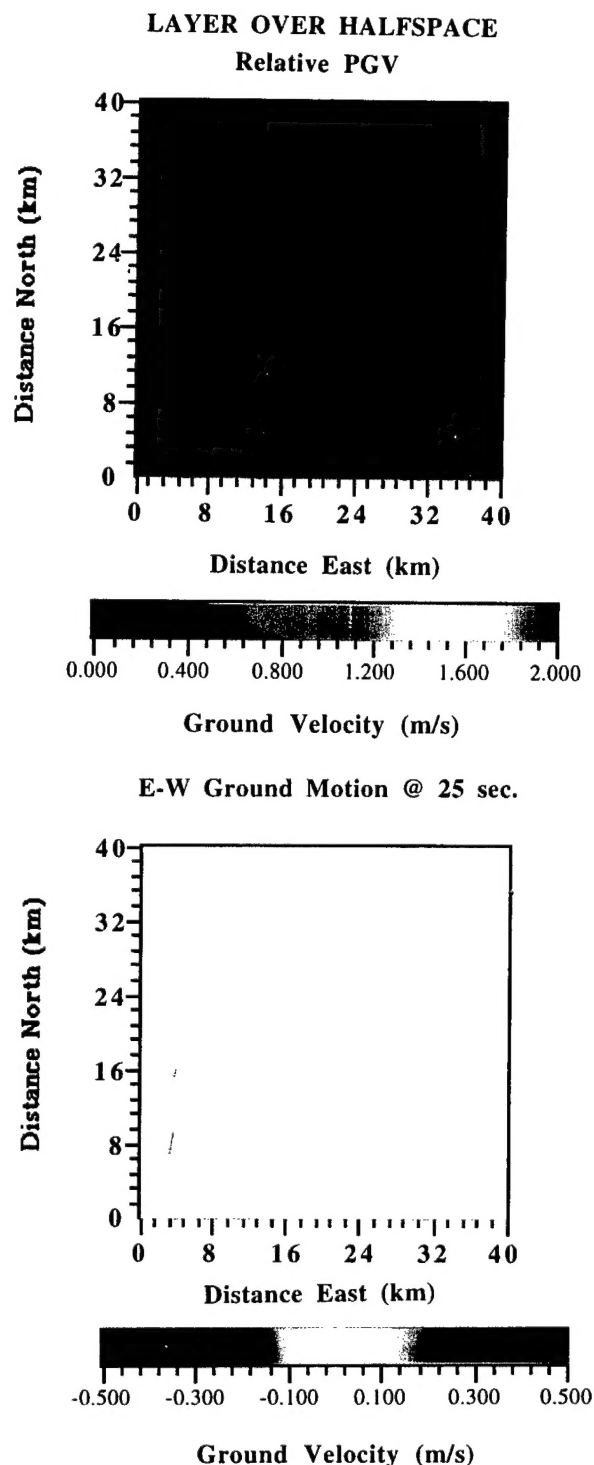


Figure 2: Peak ground velocity at the surface using a layer-over-a-half-space earth structure model (top). Snapshot of ground motion taken 25 seconds after rupture initiation (bottom). Source parameters of the hypothetical earthquake and overall dimensions of the earth model are the same as for the basin example in Figure 1. The layer-over-a-half-space model consists of a 2 km thick sedimentary rock layer over a hard rock (granite) half-space. Note the spatial uniformity of the peak ground velocity (top) and the simplicity of the ground motion (bottom).

earth's surface. In contrast, peak velocities for the 1-D model (Figure 2) are rather uniform. Also, on average, the 1-D model yields lower peak ground velocities. For the 3-D model (Figure 1), the high peak ground velocities forming the lobes of the radiation pattern in the immediate vicinity of the fault (southeast corner of the basin) is explained by the fact that the top of the fault is shallower than in the 1-D model.

The bottom frame of Figures 1 and 2 compare snapshots of the surface ground motion for the two models. Each snapshot corresponds to the wavefield 25 seconds after rupture initiation. We see that the complex pattern of ground motion associated with the basin model (bottom frame of Figure 1) stands in sharp contrast to the simple wavefield in the layer-over-a-half-space model (Figure 2). The wavefield in the 1-D model is attributed to the primary wavefront radiating outward from the source, while the wavefield in the 3-D basin model is a superposition of the primary wavefront with waves scattered by the basin structure.

Suggested future work includes expanding the volume of the basin model to ensure against possible contamination from artificial ground motion reflections generated at the absorbing boundaries. Further, a major modification of the finite difference code is the addition of anelastic attenuation operators. The interaction of anelastic attenuation with the effects of basin geometry (focusing and scattering of seismic waves) will yield a realistic estimate of the absolute levels of ground motion and refine the extent of ground motion variability associated with a sedimentary basin structure.

3. IRREGULAR-GRID MODELING

Another research project was the development of an irregular-grid method, based on a finite volume approximation, for the modeling of wave propagation in crustal models containing irregular interfaces and surface topography. This method has the advantage over finite differences in that interfaces in a model (including an irregular free surface) can be represented more accurately, and that the grid spacing can vary throughout the model and can thus be scaled to the wavespeeds.

We have implemented 2-D parallel versions of the algorithm for both SH and P-SV waves on the nCUBE 2 parallel computer of the Earth Resources Laboratory, using the Message Passing Interface (MPI). Using MPI guarantees easy portability of the codes. An efficient parallel implementation of the irregular-grid method was considerably more challenging than a parallel implementation of a finite difference algorithm, as an efficient grid decomposition (in terms of both load balancing and computation-to-communication ratio) is far more complicated for an unstructured grid.

We used the irregular-grid code to study the effect of surface topography on regional wave propagation. Figure 3a shows a 2-D crustal model with surface topography. Figure 3b shows the topography in more detail. The topography was obtained with the online profile maker from Cornell University's Middle East and North Africa Project database (<http://atlas.geo.cornell.edu>) for a profile in northern Iran.

We computed synthetic seismograms for this model with and without including the sur-

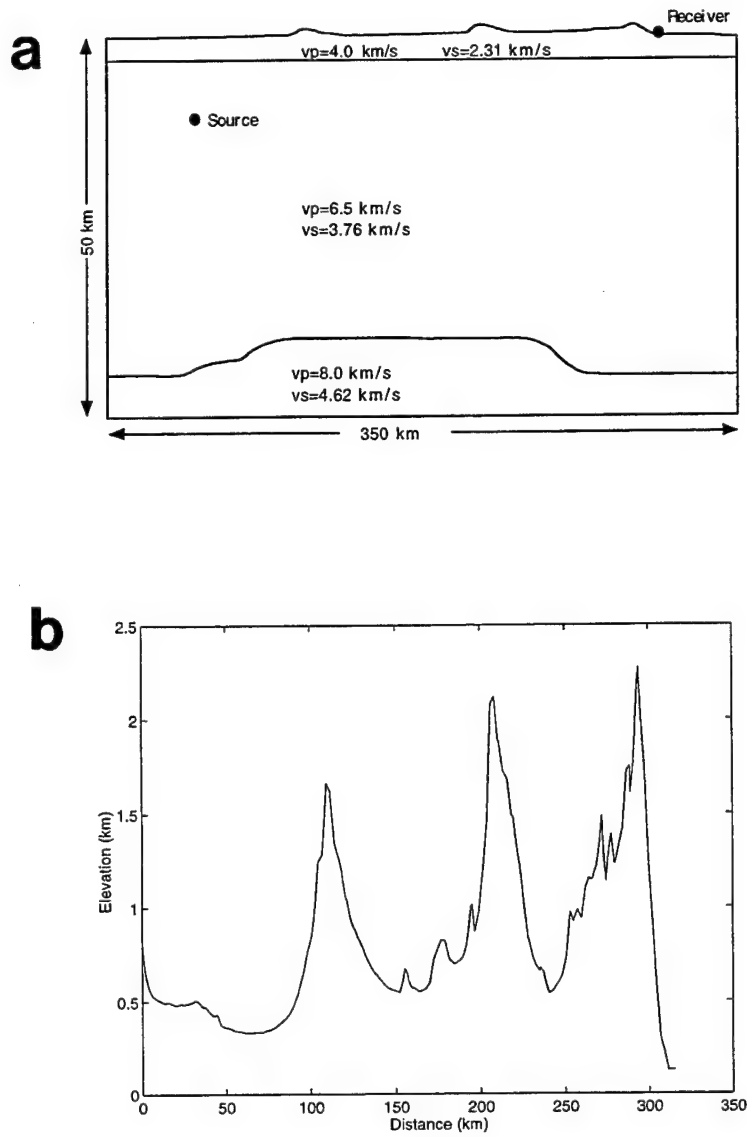


Figure 3: (a) Model with irregular surface topography used for the computation of synthetics.
 (b) Surface topography on a finer scale.

face topography. The results are shown in Figure 4. There are some distinct differences in the waveforms obtained for the two cases. In this example the most prominent differences are on the vertical component at larger arrival times (greater than 70 s). More arrivals with higher amplitudes are present in the case of surface topography. These arrivals are most likely due to surface waves that arise from scattering at the rough surface.

Our comparison demonstrates that a pronounced surface topography, such as is present in many regions (e.g., the Middle East), will have a distinct effect on observed waveforms, and should thus be included in the modeling. Our newly developed method provides a valuable tool for this task.

Suggested future work in the area of irregular-grid modeling includes the extension of the method to 3-D and its coupling to regular-grid finite differences, which will enable us to use irregular grids only in parts of the model, particular in the near-surface region. Such a hybrid approach would take advantage of the strong points of either method and thus maximize the overall efficiency.

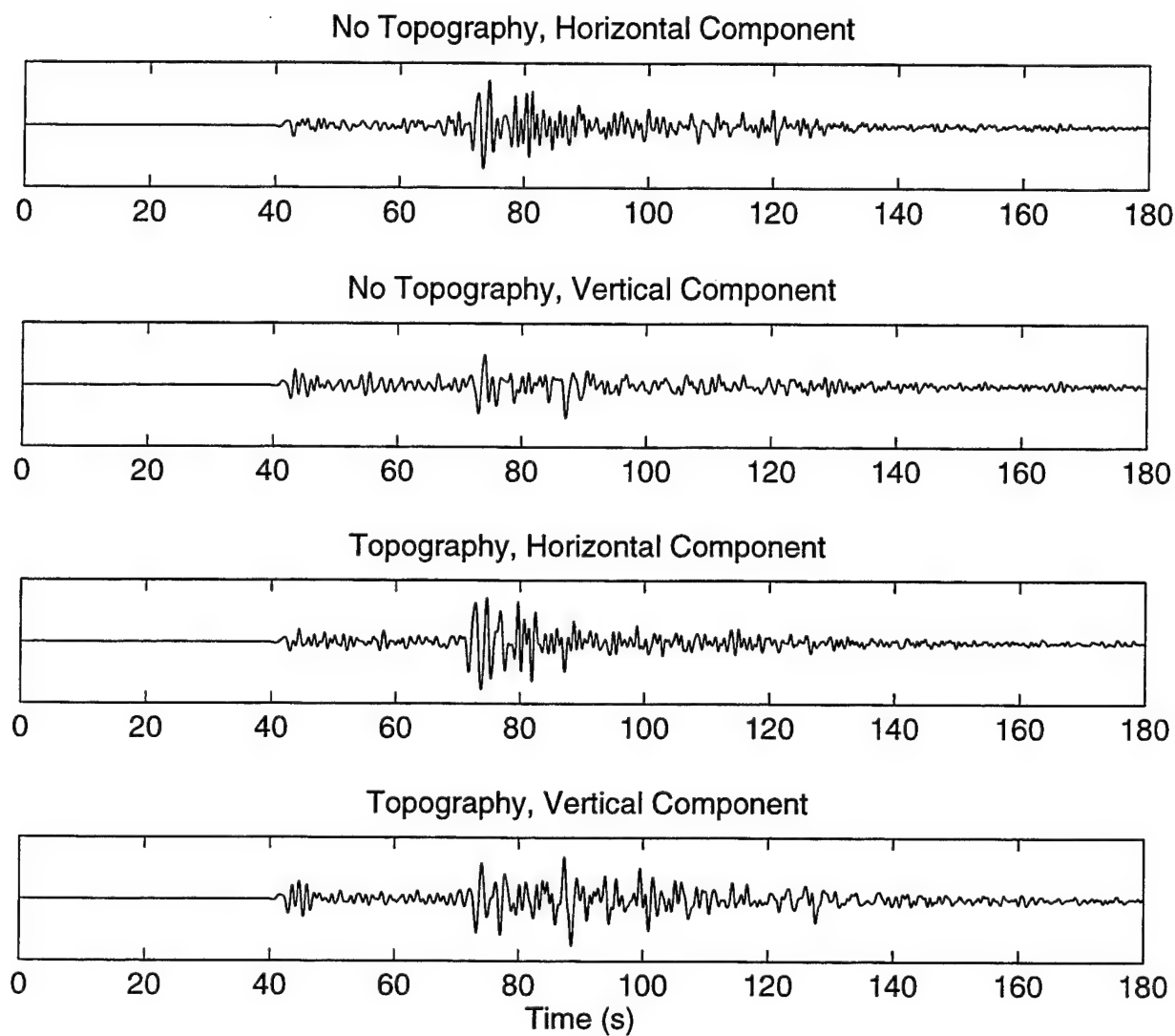


Figure 4: Synthetic waveforms on horizontal and vertical components for the model in Figure 3 and for an equivalent model with a flat surface.

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